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Photon isolation effects at NLO in $\gamma\gamma$ +jet final states in hadronic collisions

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ABSTRACT: We present the NLO QCD corrections to $pp \rightarrow \gamma\gamma j$ production at hadron colliders. Our calculation includes contributions from the fragmentation of a hadronic jet into a highly energetic photon, and consequently allows the implementation of arbitrary infrared-safe photon isolation definitions. We compare different photon isolation criteria and perform a detailed study of the dependence of the $\gamma\gamma j$ cross section on the photon isolation parameters.

KEYWORDS: QCD, Jets, Photons, Collider Physics, NLO Calculations.

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1. Introduction

Diphoton final states have played a crucial role in the recent discovery of a new boson at the LHC [1,2], and the fact that its partial decay width to photons seems to be enhanced as compared to the Standard Model (SM) Higgs boson keeps up the interest in this channel. Diphotons are also important in many New Physics searches [3–6], in particular the search for extra spatial dimensions or cascade decays of heavy new particles. In particular, diphotons in combination with jets and missing energy occur in gauge mediated SUSY scenarios.

In what concerns the SM processes at the LHC, the diphotons will most certainly be accompanied by one or more high- p_T jets, which are often suppressed by a jet veto. However, the presence of an extra jet offers better control on the separation of backgrounds and signals and more information on the interaction dynamics. Therefore a precise understanding of SM processes yielding diphotons in association with jets is mandatory.

Diphoton production has been calculated at NLO some time ago [7], supplemented also by gluon initiated subprocesses beyond the leading order [8] and soft gluon resummation [9, 10]. Recently, NNLO corrections to direct diphoton production also have become available [11]. Monte Carlo approaches to prompt photon production with matrix-element/parton-shower merging also have been studied [12–14]. In [12], the fragmentation contribution is generated by a combined QCD+QED shower, and photon isolation is done

within the democratic clustering approach [15–17]. Refs. [13, 14] contain an NLO Monte Carlo study of diphoton production, where fixed cone-based photon isolation is also possible.

NLO calculations of diphoton-plus-jet production [18], photon-plus-two-jet production in QCD production [19] and in vector boson fusion [20], and diphoton production at NNLO [11] were up to now only carried out based on a smooth-cone isolation and did not admit the implementation of alternative isolation criteria.

In this article, we present an NLO calculation of diphoton production in association with one jet which also contains a component from the fragmentation of QCD partons into photons, thereby allowing to study the effect of different photon isolation criteria. In addition, we provide a public code to compute $\gamma\gamma$ +jet final states at NLO, where the virtual amplitude has been pre-generated with the automated one-loop program GoSAM [21]. Section 2 contains a general discussion of photon isolation criteria and fragmentation. In Section 3 technical details of the calculation are discussed, while the results are presented in Section 4, before we conclude in Section 5.

2. Photon isolation criteria and photon fragmentation

Photons in hadronic final states can have multiple origins. Besides the radiation of a hard photon off a quark involved in the hard interaction (sometimes called ‘prompt’ photon), photons can also be emitted during the hadronization phase of a hadronic jet or can be the result of electromagnetic decays of unstable hadrons (these are sometimes called ‘secondary photons’). Especially the decay $\pi^0 \rightarrow \gamma\gamma$ of pions at high transverse momentum can mimic the signature of a single photon if the two photons are too closely collimated to be resolved individually. Only the production of prompt photons can be computed within perturbation theory from first principles, while the production of photons in hadronization and hadron decays can only be modeled, thereby introducing dependence on ad-hoc parameters.

Photons resulting from the hard interaction are usually well-separated from all hadronic jets produced in the event, while photons from hadronization and decay processes will always be inside hadronic jets. To disentangle prompt from secondary photons, one applies isolation requirements, which limit the hadronic activity around a photon candidate, thereby defining an “isolated photon”. A veto on all hadronic activity around the photon direction would result in a suppression of soft gluon radiation in part of the final state phase space, thereby violating infrared safety of the observables. Consequently, all photon isolation prescriptions must admit some residual amount of hadronic activity around the photon direction.

By admitting some hadronic activity around a photon, one includes final state configurations with a final state quark radiating a highly energetic collinear photon. These configurations contain a collinear singularity, related to small invariant masses of the quark-photon system. Mass factorization in QCD relates this singularity to a redefinition of the quark-to-photon fragmentation function, which describes the production of a photon inside a hadronic jet. Like parton distributions in the proton, these fragmentation functions

are non-perturbative objects that have to be determined from experimental observations. Their dependence on the resolution scale is governed by evolution equations.

The fragmentation contribution intertwines the production of prompt and secondary photons. An observable with final state photons defined through isolation criteria will typically receive some contribution from photon fragmentation, with the isolation criterion aiming to minimize this contribution. Several isolation criteria were proposed in the literature and applied in experimental studies of single photon and photon pair production.

The cone-based isolation is most commonly used especially at hadron collider experiments. In this procedure, the photon candidate is identified (prior to the jet clustering) from its electromagnetic signature, and its momentum direction (described by transverse energy $E_{T,\gamma}$, rapidity η_γ and polar angle ϕ_γ) is determined. Around this momentum direction, a cone of radius R (typically chosen around 0.4) in rapidity η and polar angle ϕ is defined. Inside this cone, the hadronic transverse energy $E_{T,\text{cone}}$ is measured. The photon is called isolated if $E_{T,\text{cone}}$ is below a certain threshold, defined either in absolute terms, or as fraction of $E_{T,\gamma}$ (typically 0.1 or below). The latter criterion then means that a photon candidate is considered as isolated if in a cone defined by

$$(\eta - \eta_\gamma)^2 + (\phi - \phi_\gamma)^2 \leq R^2 ,$$

the amount of hadronic energy does not exceed a pre-defined fraction of the photon energy:

$$E_{\text{had}} \leq \epsilon_c p_T^\gamma . \quad (2.1)$$

An alternative to the cone-based isolation is the democratic clustering procedure [15]. In this procedure, a photon candidate is treated like any hadron in the jet recombination, which can be performed using any (cone-based or clustering based) infrared-safe jet algorithm [22]. After the jet recombination, jets containing photons are labeled as photon jets, which are identified as isolated photons if the photon energy in the jet exceeds a predefined fraction z_{cut} of the jet energy. Typical values of z_{cut} are 0.9 or above.

Both cone-based isolation and democratic clustering admit some fraction of events involving collinear quark-photon systems. The theoretical predictions for cross sections defined in these procedures must therefore take account of photon fragmentation contributions.

Finally, the smooth cone isolation criterion [23] varies the threshold on the hadronic energy inside the isolation cone with the radial distance from the photon. It is described by the cone size R , a weight factor n and an isolation parameter ϵ . With this criterion, one considers smaller cones of radius r_γ inside the R -cone and calls the photon isolated if the energy in any sub-cone does not exceed

$$E_{\text{had,max}}(r_\gamma) = \epsilon p_T^\gamma \left(\frac{1 - \cos r_\gamma}{1 - \cos R} \right)^n . \quad (2.2)$$

In theoretical studies, typical values used for the smooth cone isolation parameters are $R = 0.4$, $\epsilon = 0.5$, $n = 1$. By construction, the smooth cone isolation does not admit any hard collinear quark-photon configurations, thereby allowing a full separation of direct

and secondary photon production, and consequently eliminating the need for a photon fragmentation contribution in the theoretical prescription. Despite this advantage, the smooth cone isolation was up to now used in experimental studies of isolated photons only in a discretized approximation [24]. Owing to finite detector resolution, an implementation will only be possible to some minimal value of r_γ , thereby leaving potentially a residual collinear contribution.

Perturbative calculations of isolated photon production must take proper account of the isolation criterion used to define the observable. Besides the usual higher-order QCD effects from unresolved partonic radiation, these calculations must also take account of the quark-photon collinear singularity appearing in the photon isolation procedure. In some specific observables (inclusive photon production in e^+e^- -annihilation [25, 26] and deep inelastic scattering [27–30] as well as photon-plus-one-jet production in e^+e^- [15, 16, 31, 32] and photon-plus-no-jet production in deep inelastic scattering [30]), this singularity appears already at the leading order [15, 27]. These observables are consequently most sensitive to the photon fragmentation function and can thus be used for its determination [17, 33].

Concerning the counting of perturbative orders, some ambiguity arises when photon fragmentation contributions are present. The photon fragmentation function itself is $\mathcal{O}(\alpha)$. Its evolution equation differs from the evolution equations for the fragmentation functions of hadrons [34] by a direct term, which results in logarithms of the resolution scale not being suppressed by one order of the strong coupling constant (as in the case of hadron fragmentation). Motivated by this difference, it has been argued that the photon fragmentation function should be assigned an inverse power of the strong coupling constant [35–37], thereby shifting the relative order of direct and fragmentation contributions. Viewed by mass factorization counter terms (and infrared finiteness of the observables), the photon fragmentation function does not require an inverse power of the strong coupling constant. In calculations of electroweak corrections to jet observables [38–41] where similar photon isolation issues appear, the photon fragmentation function is consistently taken as $\mathcal{O}(\alpha)$.

Single photon and diphoton production at hadron colliders receive contributions from collinear quark-photon splitting only at next-to-leading order in perturbation theory. Among the existing calculations of NLO corrections to photon pair production [7–9] and photon-plus-jet production [42, 43], the ones in [7, 42, 43] have implemented both cone-based and smooth cone isolation and assume the power counting of the photon fragmentation function to contain an inverse power of the strong coupling constant, which means that a multitude of fragmentation subprocesses have to be (and have been) included at NLO. In general, these subprocesses are however of rather minor impact on the total result after isolation cuts, owing to the overall smallness of fragmentation contributions in these observables. For the purpose of our calculations, we will therefore use a power counting of the photon fragmentation function as $\mathcal{O}(\alpha)$.

3. NLO corrections to $pp \rightarrow \gamma\gamma + \text{jet}$ final states

3.1 Structure of the calculation

The calculation of the NLO corrections to $pp \rightarrow \gamma\gamma + \text{jet}$ requires the combination of the full

QCD corrections with counter terms regularizing infrared QED singularities. In a first step we produced a code that is able to calculate the QCD corrections. For generation of the tree level and real emission matrix elements we use MadGraph [44,45], the regularisation of infrared QCD singularities is handled by MadDipole [46,47], which makes use of the dipole formalism as developed in [48]. For integration over the phase space we used MadEvent [49]. The routines for generating histograms and distributions originate from the MadAnalysis package (see <http://madgraph.hep.uiuc.edu>).

The generation of the various pieces and their combination for the phase space integration has been done in a fully automated way.

3.2 Calculation of the virtual corrections

The virtual corrections have been calculated with the automated one-loop amplitude generator GoSAM [21]. The program package GoSAM starts from an input card edited by the user and generates the diagrams and the corresponding expressions for the loop amplitudes in an automated way, using QGRAF [50], FORM [51,52] supplemented with Spinney [53] for the spinor algebra, and haggies [54] for the automated code generation. It combines unitarity-inspired integrand reduction techniques [55–59] with traditional tensor reduction methods [60,61]. The rational part can be calculated algebraically within GoSAM in an automated way.

We generated two versions of the virtual contributions, with and without top loops and found the effects of virtual top quarks negligible. Therefore the results presented here have been obtained without the top contributions. Furthermore, we neglect one loop contributions with two initial state gluons, which are formally of higher order, as there is no corresponding tree level amplitude. Their contribution may potentially be enhanced by the large gluon luminosity [7,8]. Their inclusion is however beyond the scope of this paper.

The remaining contributions can be reduced to the virtual corrections for the process

$$q\bar{q} \rightarrow \gamma\gamma g. \quad (3.1)$$

The complete set of virtual corrections can be obtained from eq. (3.1) by crossing of the momenta and/or changing overall factors for different electromagnetic charges. In total there are 130 diagrams to be calculated up to pentagons. The virtual amplitude has been checked for gauge invariance by adding a momentum dependent part to the photon polarisation vectors.

3.3 Calculation of real radiation contributions

As explained in detail in Section 2 above, the QCD corrections for processes involving photons contain infrared singularities related to the collinear emission of the photon off a final-state QCD parton. These singularities are compensated by the mass factorization terms of the photon fragmentation functions.

From the computational point of view this implies that the real emission matrix element contains collinear singularities which need to be regularized by some kind of subtraction terms. The corresponding integrated subtraction terms make this singularity apparent as

they develop an explicit pole term when integrated over the unresolved one-particle phase space in dimensional regularisation. This pole is then absorbed into the fragmentation functions. To regulate these singularities we again make use of the dipole formalism as developed in [62] and implemented in the QED extension of MadDipole [63]. This extension also offers the framework for a straightforward implementation of fragmentation functions. We refer to [63] for further details.

A collinear singularity between a photon and a quark can be regulated by a single dipole. Note that in principle the role of emitter and unresolved particle is interchanged. In a true QED calculation the quark would be the emitter and the photon the unresolved particle. However in this calculation the photon is a tagged particle whereas the additional jet can be unresolved. Nevertheless the dipole formalism for QED can be used as the subtraction terms are symmetric under the exchange of emitter and unresolved particle if both are massless. A small modification has been made in such a way that also photons are allowed as spectators. This ensures that one can always use final-final dipole configurations, thereby reducing the complexity of the calculation.

Upon phase space integration, the pointwise cancellation of the infrared poles from the virtual amplitude with those from the real radiation part has been checked. For both QCD and QED subtraction terms we have checked the independence on the α -parameter [64], which restricts the phase space segments on which dipole subtraction is performed to the vicinity of the infrared singularities. To perform this check we had to extend the usage of the α -parameter to the QED subtraction terms for non-collinear safe observables. In the purely massless case and for final-final configurations this extension is straightforward.

NLO corrections to $\gamma\gamma$ +jet final states for the Frixione isolation criterion are free of collinear quark-photon contributions and do not depend on the photon fragmentation function. For this specific isolation criterion, NLO results for $\gamma\gamma$ +jet production have been derived in [18]. We fully reproduce these results, thereby obtaining a strong check on the correctness of our implementation of the virtual and real matrix elements, as well as on the non-QED-type subtraction terms.

4. Numerical results

In this section we present phenomenological results for proton-proton collisions at $\sqrt{s} = 8$ TeV. The results are divided into two categories: the one-jet inclusive case, $pp \rightarrow \gamma\gamma$ +jet+ X , and the one-jet exclusive case $pp \rightarrow \gamma\gamma$ +jet. The inclusive sample is defined by requiring that at least one jet in the event passes the selection cuts introduced below, while the exclusive sample admits only events containing exactly one jet within the selection cuts.

4.1 Input parameters and kinematic cuts

For the jet clustering we used an anti- k_T algorithm [65] with a cone size of $R_j = 0.4$ provided by the **FastJet** package [66, 67]. We used an NLO parton distribution set from NNPDF2.3 [68], where the values for α_s at leading order and next-to-leading order are

given by

$$\alpha_s(M_Z) = 0.119 ,$$

and the running is calculated at one loop for the LO results and at two loops for the NLO results. For the photon fragmentation functions, we take set II of the parametrisations of Ref. [37].

The following kinematic cuts have been applied: $p_T^{\text{jet}} > 40 \text{ GeV}$, $p_T^\gamma > 20$, $|\eta^\gamma, \eta^j| \leq 2.5$, $R_{\gamma,j} > 0.4$, $R_{\gamma,\gamma} > 0.8$ and $100 \text{ GeV} \leq m_{\gamma\gamma} \leq 140 \text{ GeV}$. The intention of the latter cut is to focus on a region around the Higgs resonance.

For the photon isolation, we compare the Frixione isolation criterion with the fixed cone criterion for several values of the photon energy fraction ϵ_c in the cone. For the Frixione isolation criterion (see eq. (2.2)), our default values are $R = 0.4, n = 1$ and $\epsilon = 0.5$. For the cone-based isolation, the default cone size is $R = 0.4$, while several different values of the hadronic energy fraction z_c inside the cone will be used, where

$$z_c = \frac{|\vec{p}_{T,\text{cone}}^{\text{had}}|}{|\vec{p}_T^\gamma + \vec{p}_{T,\text{cone}}^{\text{had}}|} ,$$

such that in the collinear limit, z_c is related to ϵ_c in eq. (2.1) by $z_c = \frac{\epsilon_c}{1+\epsilon_c}$.

4.2 Scale dependence and sensitivity to the isolation parameters

The truncation of the perturbative expansion of a collider observable leads to a dependence on scale parameters that were introduced in the renormalization and mass factorization. The residual dependence on these parameters is often used to quantify the uncertainty on the calculation from missing higher order terms in the perturbative series. Apart from the dependence on renormalization and initial state factorisation scales μ_r, μ_f , the cross section for the production of prompt photons also depends on the fragmentation scale μ_F , as explained in section 2 above. To study the scale dependence of our NLO results, we set $\mu_r = \mu_f = \mu_F$ and choose $\mu_0^2 = \frac{1}{4} (m_{\gamma\gamma}^2 + \sum_j p_{T,j}^2)$ for our central scale. The scales are then varied by $\mu = x \mu_0$ with $0.5 \leq x \leq 2$.

In Figure 1, we display the scale dependence of the exclusive $\gamma\gamma$ +jet cross section. For a cone-based isolation criterion, we observe a clear reduction of the scale dependence at next-to-leading order, while this reduction is less pronounced for the Frixione isolation criterion. This qualitative difference can be attributed to the occurrence of almost collinear quark-photon configurations at NLO. The typical scale of these configurations is the invariant mass of the quark-photon system, which can be substantially lower than μ_0 . In the case of a cone-based isolation, these contributions combine with the fragmentation contribution, which compensates their scale dependence. For the Frixione isolation criterion, this compensation does not occur, thereby resulting in a larger scale-dependence.

In the inclusive case, Fig. 2, no reduction of the scale uncertainty at NLO is visible. The reason for this is the fact that the cross section in this case is dominated by the $\gamma\gamma$ +2jets real radiation part, which shows a leading order scale dependence. A similar behaviour has been observed for example in ZZ +jet production with and without second jet veto [69]. The largeness of the NLO corrections has already been observed for Frixione isolation

in Ref. [18]. The reasons are the appearance of new partonic subprocesses at NLO and the enlarged final state phase space at this order.

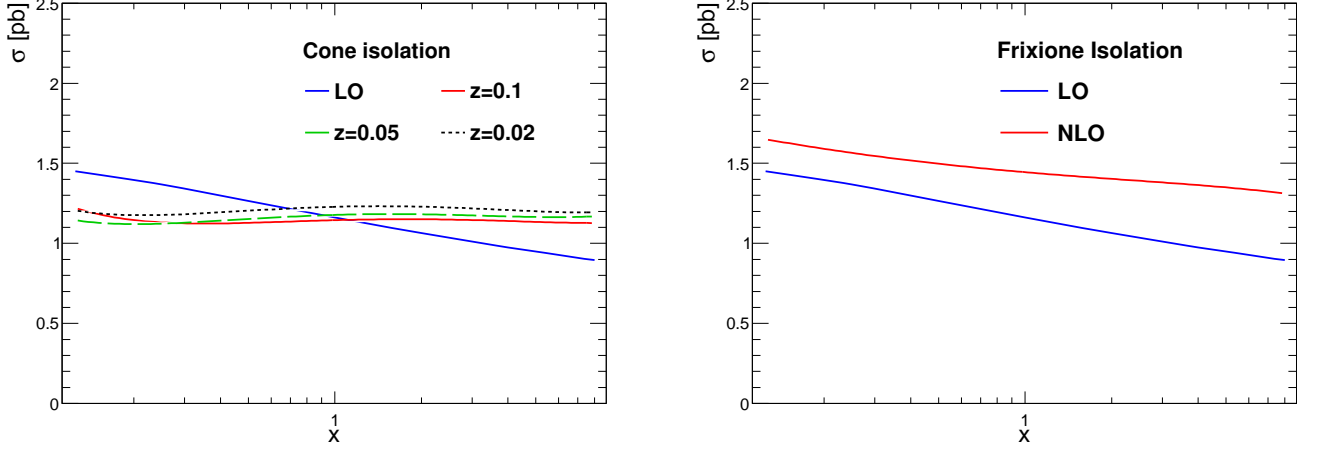


Figure 1: Behaviour of the exclusive $\gamma\gamma$ +jet cross sections with different isolation prescriptions under scale variations, $\mu = x \mu_0$, $0.5 \leq x \leq 2$, $\mu_0^2 = \frac{1}{4} (m_{\gamma\gamma}^2 + \sum_j p_{T,j}^2)$.

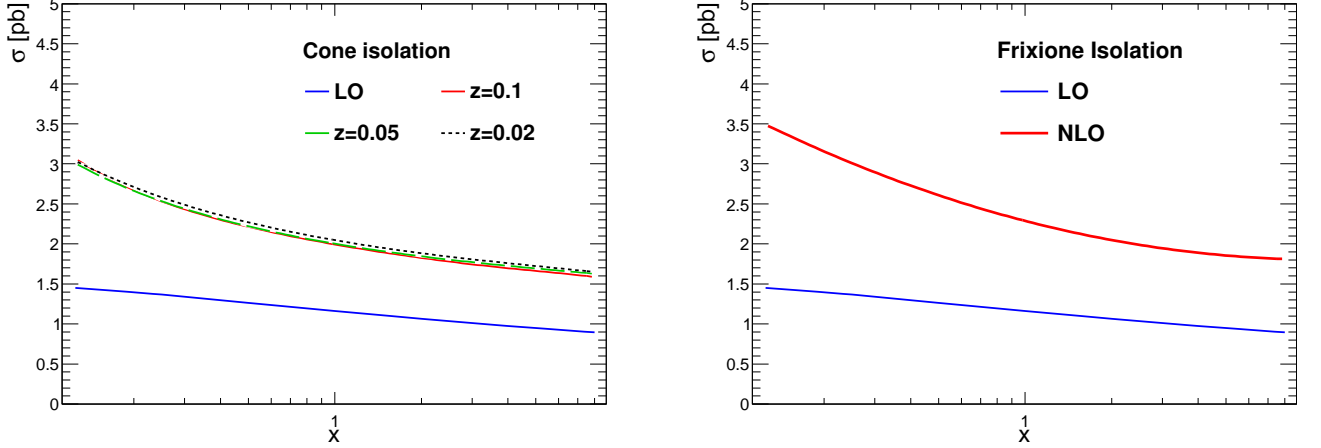


Figure 2: Behaviour of the inclusive $\gamma\gamma$ +jet+X cross sections with different isolation prescriptions under scale variations, $\mu = x \mu_0$, $0.5 \leq x \leq 2$, $\mu_0^2 = \frac{1}{4} (m_{\gamma\gamma}^2 + \sum_j p_{T,j}^2)$.

Due to photon isolation, the cross section for $pp \rightarrow \gamma\gamma$ +jet+X is not strictly an inclusive quantity. The integration over the final state collinear variable z appearing in the fragmentation functions $D_q^\gamma(z, \mu_F)$ is bounded from below by $1 - z_c$.

Further, the presence of three different scales μ_r, μ_f, μ_F partially leads to a scale dependence which is different from what is known from pure QCD.

Figures 3 and 4 show how the scale variation bands vary as a function of the isolation parameters, for both the single-jet inclusive and the exclusive case. One observes that

for both isolation criteria the inclusive case is dominated by the large scale dependence of the $\gamma\gamma + 2\text{jets}$ part of the real radiation which has an uncompensated leading order scale dependence.

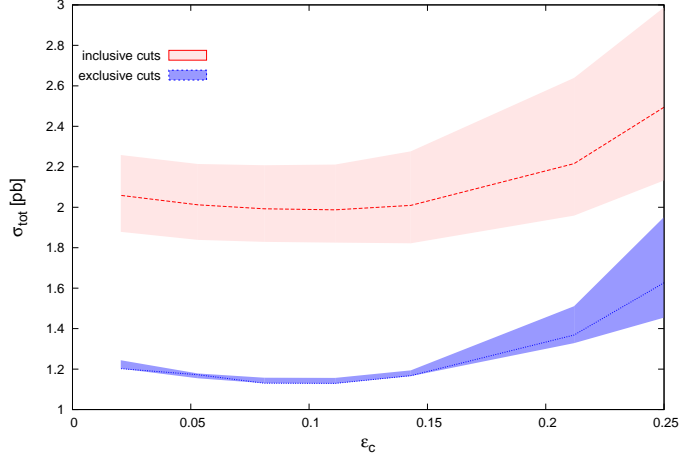


Figure 3: Dependence of the cross sections on the cone isolation parameter ϵ_c . The bands correspond to scale variations $0.5 \leq x \leq 2$, with $\mu = x \mu_0$.

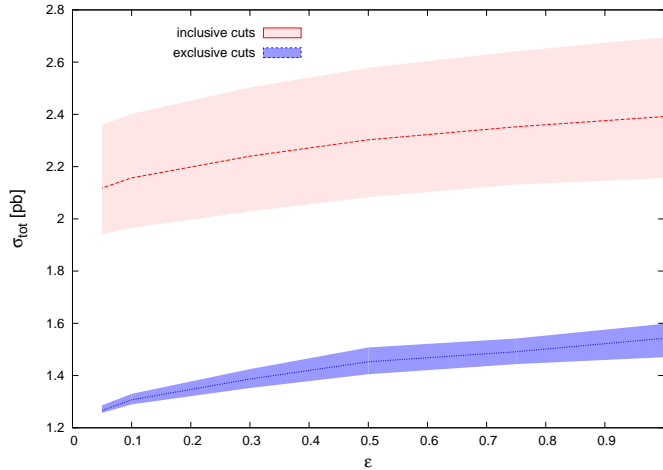


Figure 4: Dependence of the cross sections on the Frixione isolation parameter ϵ .

Comparing Fig. 3 and Fig. 4, it can be seen that the qualitative dependence on the hadronic energy threshold parameters ϵ_c (in fixed cone isolation) and ϵ (in Frixione isolation) is substantially different. In particular, we observe the onset of a sizeable increase in the cross section for $\epsilon_c > 0.15$ (corresponding to a hadronic energy fraction in the fixed cone larger than 15%), while for Frixione isolation, the cross section increases only mildly over the interval $0.1 < \epsilon < 1$. This difference in the qualitative behaviour shows that the parameters can not be translated into each other, since the threshold in the fixed cone isolation is rigid, while the threshold in the Frixione isolation is dynamical, and weighted by the distance to the cone axis. The strong increase for the fixed cone isolation thus

comes from radiation that is very close to the cone axis (and from fragmentation), which is suppressed by the Frixione criterion.

The small size of the scale variation band for $\epsilon_c \lesssim 0.14$ in the case of exclusive cuts with cone isolation can be understood from the fact that in this range of z , the $\log(\mu_F)$ terms which are contained in the perturbative component of the fragmentation functions largely cancel the μ_F dependence of the direct real radiation part. Only for larger ϵ_c values non-perturbative and beyond-leading-logarithmic effects start to become important. We validated this cancellation in detail on the NLO corrections to diphoton production, as implemented in the code DIPHOX [7].

With Frixione isolation, the $\log(\mu_F)$ dependence is absent, therefore the behaviour under scale variations in Fig. 4 is qualitatively different.

4.3 Results for diphoton plus one jet production – exclusive case

In the exclusive case, only moderate NLO corrections are observed in the kinematical distributions related to $\gamma\gamma$ +jet final states. Figure 5 displays the photon pair invariant mass and the jet transverse momentum distributions. We observe that the NLO corrections are in general limited in magnitude, and slightly larger for the Frixione isolation than for the cone-based isolation. Inclusion of the NLO corrections amounts to an rescaling of the distributions that is constant in invariant mass, and slightly decreasing with jet transverse momentum.

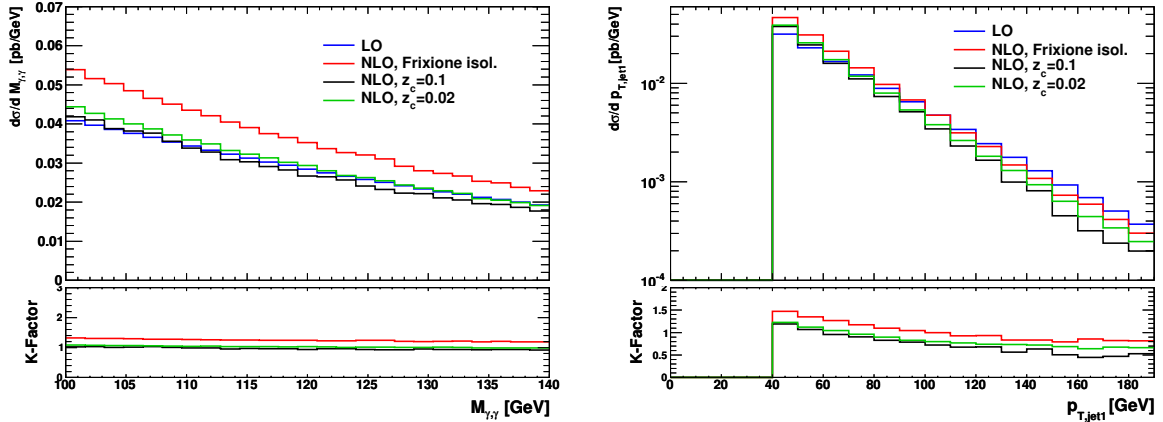


Figure 5: (a) Photon invariant mass distribution, (b) transverse momentum distribution of the leading jet for the diphoton plus one jet exclusive cross section.

In Figure 6, the transverse momentum distributions of the leading and the subleading photon are displayed. It can be seen that the leading- p_T photon tends to become softer at NLO, which is natural since the additional QCD radiation carries away momentum.

Figure 7 shows the differential distributions in the distance $R_{j\gamma} = \sqrt{(\eta^j - \eta^\gamma)^2 + (\phi^j - \phi^\gamma)^2}$ between the jet and the harder photon (γ_1) respectively the softer photon (γ_2), with a separation cut of $R_{j\gamma} \geq 0.4$. At leading order, the preferred kinematical configuration of the jet is back-to-back with the harder photon, and near to the softer photon. These kinematical correlations are weakened with the inclusion of NLO corrections, with an increase of events

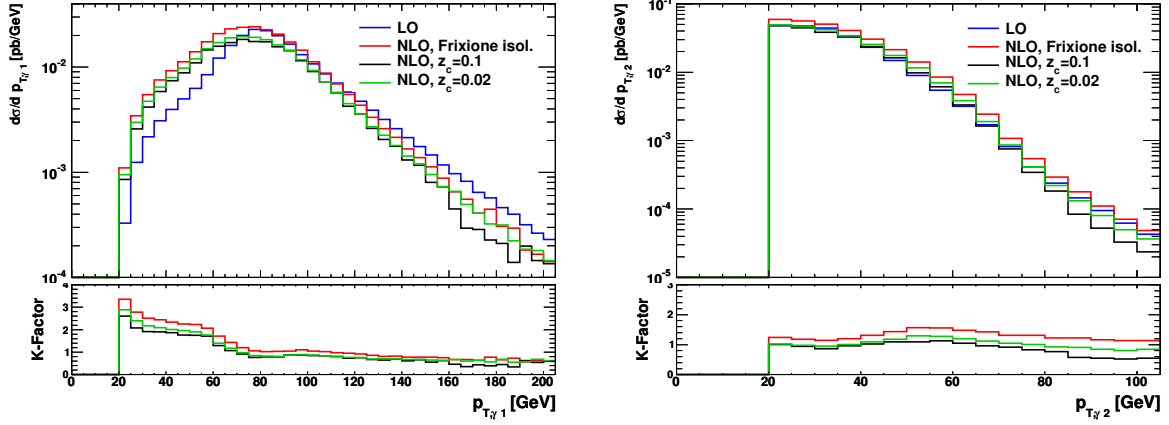


Figure 6: Transverse momentum distributions of the leading (i.e. larger- p_T) and subleading photon for the diphoton plus one jet exclusive cross section.

with smaller opening angle between the hard photon and the jet or larger opening angle between the soft photon and the jet.

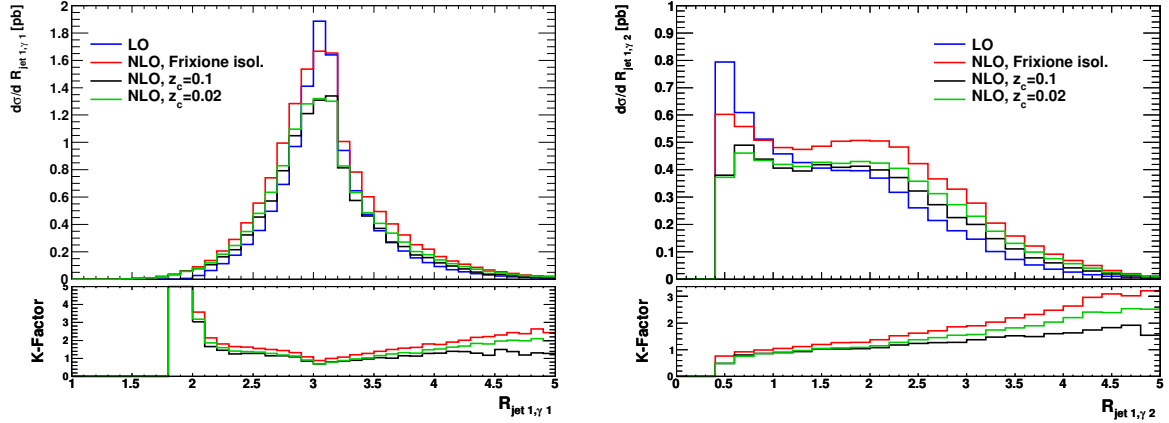


Figure 7: R -separation between photon and jet in the $\eta - \phi$ plane for the diphoton plus one jet exclusive cross section. $R_{jet1,\gamma1}$ denotes the R -separation between the jet and the harder photon, while $R_{jet1,\gamma2}$ is the R -separation between the jet and the softer photon.

4.4 Results for diphoton plus one jet production – inclusive case

As already observed for the total cross section, NLO corrections are substantially larger for the inclusive cross section $\gamma\gamma+\text{jet}+X$ as compared to the exclusive case. In the inclusive cross section, the substantial contribution from $\gamma\gamma + 2$ jet final states results in larger corrections, and induces substantial modifications to some of the kinematical distributions.

Figure 8 displays the inclusive distributions in photon pair invariant mass and leading jet transverse momentum. The magnitude of the corrections is larger than in the exclusive case, they remain constant for the invariant mass distribution and rise with the jet transverse momentum (as opposed to the decrease with jet transverse momentum in the exclusive case, Figure 5). Again, the corrections for the Frixione isolation criterion are slightly larger than for the fixed-cone isolation.

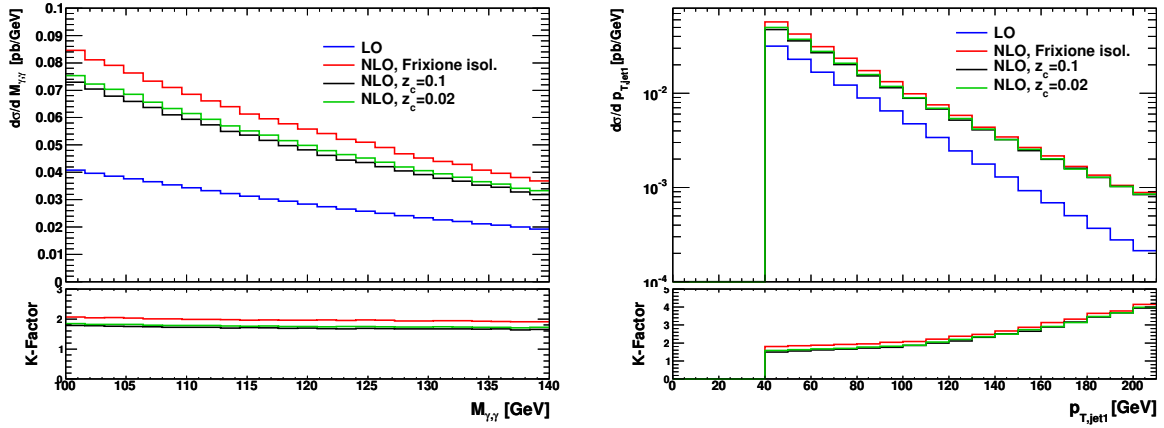


Figure 8: (a) Photon invariant mass distribution, (b) transverse momentum distribution of the leading jet for the diphoton plus one jet inclusive cross section.

The photon transverse momentum distributions, Figure 9, display a similar behaviour as in the exclusive case, with the main effect from NLO corrections appearing in a softening of the leading photon distribution. The effect of the extra jet in the inclusive distribution is particularly pronounced in the $R_{j\gamma}$ distributions.

Comparing exclusive (Fig. 7) and inclusive (Fig. 10) cases, one can see very clear differences. For example, in the first bins of the $R_{j\gamma_1}$ distribution (separation between leading jet and harder photon), the inclusive case shows a shoulder due to the contributions from the second jet, which is vetoed in the exclusive case. Further, in the first bins of the $R_{j\gamma_2}$ distribution (separation between leading jet and softer photon), the K-factor is smaller than one in the exclusive case, while it is always larger than unity in the inclusive case. Note however that in the inclusive case, events where both jets fulfill the cuts are counted twice. Therefore it is somewhat misleading to directly compare K-factors between the inclusive and exclusive case.

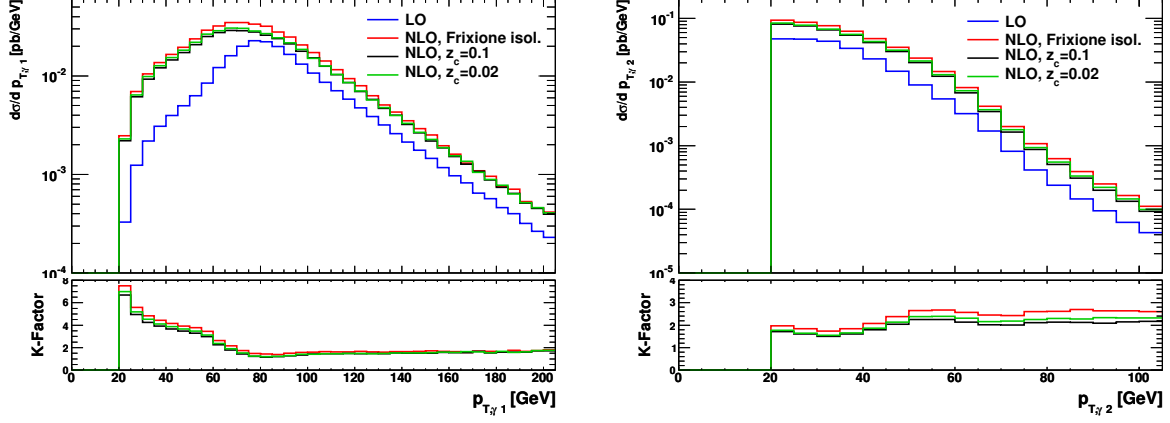


Figure 9: Transverse momentum distributions of the leading (i.e. larger- p_T) and subleading photon for the diphoton plus one jet inclusive cross section.

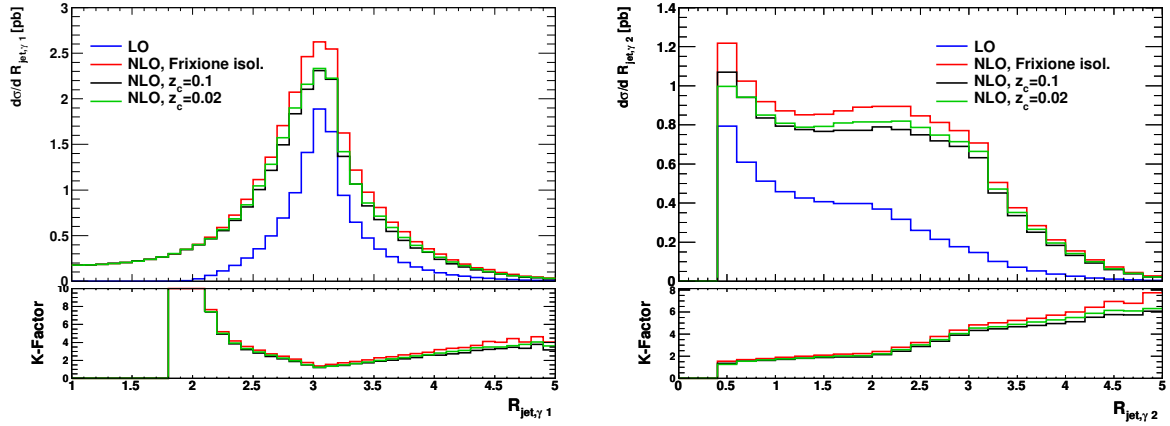


Figure 10: R -separation between photon and jet in the $\eta - \phi$ plane for the diphoton plus one jet inclusive cross section. R_{jet,γ_1} denotes the R -separation between the jet and the harder photon, while R_{jet,γ_2} is the R -separation between the jet and the softer photon.

5. Conclusions and outlook

We have calculated the NLO QCD corrections to the production of two isolated photons in association with a jet at hadron colliders. Results for both the one-jet inclusive case as well as the case where exactly one jet passing the jet selection criteria have been presented. Our calculation also includes contributions from the fragmentation of a hadronic jet into a large- p_T photon at order $\alpha^2\alpha_s^2$, and therefore allows to compare different photon isolation criteria. Comparing the Frixione isolation criterion to standard cone isolation for several values of the hadronic energy allowed in the cone, we observe that the scale dependence stabilizes at NLO for the exclusive cross section in the standard cone isolation case, while with Frixione isolation the stabilisation is much less pronounced. This behaviour can be attributed to the fact that there are cancellations of logarithms stemming from the factorisation of collinear quark-photon splittings between the direct and the fragmentation contributions. For very strict isolation parameters, the results for standard cone and Frixione isolation are similar with regards to the scale dependence. The K-factors are in general larger with Frixione isolation than with cone isolation.

In contrast to the exclusive cross section, the one-jet inclusive cross section does not show a stabilisation of the scale dependence, independent of the choice of the isolation criterion. This can be understood from the fact that the cross section in this case is dominated by the two-jet contribution of the NLO real radiation part, which shows a leading order scale dependence.

The code which is underlying the calculation presented here has been made publicly available at <http://gosam.hepforge.org/diphoton>. This will allow further dedicated studies of different isolation prescriptions and kinematic situations, and eventually the combination of the NLO calculation with a parton shower.

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